

A New (Old) Component of the Galaxy as the Origin of the Observed LMC Microlensing Events

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ABSTRACT

We suggest a new component of the Milky Way galaxy that can account for both the optical depth and the event durations obtained by the MACHO microlensing survey toward the Large Magellanic Cloud. This component is consistent with recent evidence for a significant population of faint white dwarf stars, detected in a proper motion study of the Hubble Deep Field, which cannot be accounted for by stars in the disk or spheroid. This new component consists of (mostly) old white dwarf stars distributed in a highly extended (very thick) disk configuration. It extends beyond the traditional thin and thick disks, but well within the dark, roughly spherical CDM halo. The total mass in this component is $\sim 7 - 9 \times 10^{10} M_{\odot}$. We argue that such a component is reasonable, natural, consistent with a variety of observations, and many of the problems associated with a significant halo population of white dwarfs are ameliorated.

Subject headings: dark matter — MACHOs — white dwarfs

1. Introduction

From a comparison of the amount of matter associated with the luminous components of galaxies (Faber & Gallagher 1979) and constraints from big bang nucleosynthesis (Burles et. al 1999), it is clear that most of the baryons in the Universe today are dark. A large fraction of this baryonic dark matter may be in the form of hot, diffuse gas (Gates, Gyuk, Holder & Turner 1998, Fukugita, Hogan & Peebles 1998), but dark compact objects assumed to reside in the halos of galaxies (MACHOs) are also candidates for baryonic dark matter.

The past few years have yielded much exciting new data from observational teams searching for evidence of microlensing along several lines of sight. The results from these surveys have raised many questions. The microlensing optical depth toward the Large Magellanic Cloud (LMC) obtained by the MACHO collaboration, $\tau_{\text{LMC}} = (2.1^{+1.1}_{-0.7}) \times 10^{-7}$ (Alcock et al. 1997b), is consistent with a significant fraction of the galactic halo (20% – 40%) (Gates, Gyuk & Turner 1996) in the form of MACHOs. The duration of these events also indicates that, under the assumption of a spherical isothermal halo distribution for the MACHOs, the average MACHO mass is $\sim 0.5M_{\odot}$, with large statistical uncertainties (Alcock et al. 1997b).

Such masses suggest several candidates for the lenses including faint halo stars, white dwarfs, and black holes. Direct searches for faint halo stars have placed severe limits on their contribution to halo, requiring it to be less than about 3% (Flynn, Gould & Bahcall 1996, Graff & Freese 1996). Primordial black hole candidates require a fine tuning of the initial density perturbations, and details of QCD phase transition black hole formation remain to be worked out in order to assess their viability and mass function (Jedamzik & Niemeyer 1999). Thus in the standard halo model interpretation, white dwarfs appear to be the remaining strong candidate for the lenses.

However, other possible interpretations of the MACHO results have been proposed in order to avoid the difficulties associated with a large halo population of white dwarfs. The mass estimate for the lenses depends upon the assumed phase space distribution of MACHOs. There are large uncertainties in the halo model parameters, including the distribution and velocity structure of the dark matter, and attempts have been made to exploit these uncertain-

ties in order to obtain mass estimates from the current data that are consistent with lenses in the substellar regime (e.g. brown dwarfs). Previous work by the authors and others have examined a wide range of halo models, including flattened halos (Gyuk & Gates 1998), halos with a bulk rotational component to the velocity structure (Gyuk & Gates 1998) and halos with anisotropic velocity dispersions (Gyuk, Evans & Gates 1998). These analyses have shown that for any reasonable (smoothly varying) phase space distribution of the lenses, the implied lens mass is still much larger than the hydrogen burning limit, and thus one cannot appeal to modeling uncertainties in order to invoke brown dwarfs as candidates for the MACHOs. More recent work has found that varying the model parameters cannot produce a mass estimate from the current data greater than about $0.8M_{\odot}$, implying that neutron stars are also not likely lens candidates (Gates, Olinto and Venkatesan 1999).

Other work has explored the possibility that the lenses are not in the halo of the Milky Way. LMC self-lensing has been suggested by Sahu (1994), but recent work by Gyuk, Dalal & Griest (1999) has argued that this is unlikely. Zaritsky & Lin (1997) and Zhao (1998) have suggested an intervening population of stars toward the LMC (tidal debris or a dwarf galaxy) could be responsible for the microlensing events. Again this suggestion has been subject to much debate, and a recent paper by Gould (1999) argues strongly against such a scenario. Galactic models in which dark extensions of known populations, such as a heavy spheroid or thick disk, could be the source of the lenses were explored by Gates, Gyuk, Holder & Turner (1998). We will comment further on these models in section 3 of this paper.

However, recent results from a proper motion study of the Hubble Deep Field (HDF) (Ibata, Richer, Gilliland & Scott 1999), and from a comparison of the north and south HDF images (Mendez & Minniti 1999) have added a new piece to the puzzle. These studies provide further evidence that there may be a previously undetected population of old white dwarfs in the galaxy. This strengthens the interpretation of the MACHO lenses as white dwarfs, and thus makes the above alternatives less appealing.

Ibata et al.(1999) compared the original HDF with a second image of the same field taken approximately 2 years later, searching for proper motions of faint objects. They found 5 faint, blue objects which had a significant ($\geq 3\sigma$) shift in the centroid position

over this two year period consistent with the detection of proper motions of around 20-30 mas/yr. A third epoch of observation is planned for approximately 2-3 years after the second. Obviously, the detection of proper motions eliminates the possibility that these are extragalactic sources, and indicates that they must be relatively close by.

Using new models for white dwarf cooling (Hansen 1999), the sources detected by Ibata et al. are consistent with old ($> 12\text{Gyr}$), $0.5M_{\odot}$ white dwarfs. Hansen's model predicts that very old white dwarfs will be blue and somewhat brighter than earlier models in which white dwarfs continue to redden as they cool. Previous limits on white dwarfs in the halo were based on the older white dwarf cooling models. Ibata et al. also argue that these moving sources cannot be part of the known disk, thick disk or spheroid populations and further, that the number of sources detected is consistent with the number expected for an all white dwarf halo, although this claim is strongly dependent on many factors, especially the assumed IMF of the white dwarf progenitor population (Richer 1999).

Mendez & Minniti (1999) compared faint blue point sources in HDF-North and HDF-South. They find 5 such objects in HDF-North and 10 in HDF-South. The core of their argument is that this distribution is inconsistent with distant extra-galactic sources, where an equal number would be expected for an isotropic Universe. However, a ratio of ~ 2 is roughly consistent with that expected for a galactic population since HDF-North looks toward the outer Galaxy while HDF-South is pointed more towards the center of the Galaxy. Mendez & Minniti also state that these sources represent $\sim 1/3 - 1/2$ of the dark matter in the Galaxy.

While these new data are still somewhat preliminary, they do raise the intriguing possibility that there is a previously undetected population of white dwarf stars that are not part of the disk or (known) spheroid. These new results, along with the MACHO data and the inability of modeling to significantly change the mass estimates, seems to be relentlessly pointing to white dwarfs as the lenses. So, is the halo of our galaxy filled with white dwarfs? A standard halo interpretation of these data would say yes – a significant fraction of the galactic halo must be in white dwarfs. However, such a scenario faces serious challenges from many directions, especially given the claim that the number of white dwarfs detected by

proper motion studies is large enough to imply that approximately half to essentially all of the halo is in the form of white dwarf stars.

2. White Dwarfs in the Halo?

When considering the possibility that a large fraction (or all) of the galactic halo might be in the form of white dwarfs, it is extremely important to recall the evidence for galactic dark matter, including estimates of the total mass of the Milky Way. A recent analysis of satellite radial and proper motions by Wilkinson and Evans (1999) found a total mass of the Galaxy $M_{TOT} \sim 2 \times 10^{12}M_{\odot}$, in good agreement with other recent estimates (Kochanek 1996, Zaritsky 1998). Wilkinson and Evans also find that the halo extends to at least 100kpc, and possibly much further to 150 or 200 kpc. Thus the total mass in a white dwarf population that comprises a significant fraction of the halo would be of order $10^{12}M_{\odot}$, a number which already severely strains the baryon budget of the Universe.

Models which propose such a population must also account for the mass in the progenitor population of stars and in the metal enriched gas produced during the formation of the white dwarfs. Combined with the above mass estimate for the galactic halo, such considerations provide serious challenges for these models. For example, consider a white dwarf halo which is comprised of at least 50% white dwarfs. The total mass in white dwarfs today is thus of order 10^{12} . The efficiency $\epsilon(m)$ for producing a white dwarf from a progenitor star of mass m is likely to be 0.25 or smaller, depending on the progenitor mass (with an upper limit of $\epsilon = 0.5$ for progenitor stars of $1M_{\odot}$) (Adams & Laughlin 1996). Thus, for a white dwarf halo mass of M_{wd} , we expect a mass in the progenitor population $M_{Pstars} \geq 4M_{wd}$ and a mass in processed, metal rich gas $M_{zgas} \geq 3M_{wd}$. A halo of mass $M_{TOT} = 2 \times 10^{12}$, half of which is in white dwarfs, requires a progenitor mass of $M_{Pstars} \geq 4 \times 10^{12}$. This in turn requires an extremely efficient early burst of star formation, through which essentially all of the baryons in the Universe are processed.

From a cosmological point of view, we can consider the contribution of the white dwarfs and the progenitor population to the matter density of the Universe. The Milky Way has a mass to light ratio $M/L \sim 100$ or greater (Zaritsky 1998). If we assume that this is a typical value for all galaxies, then galax-

ies contribute $\Omega_g \gtrsim 100/1200h = 0.08h^{-1}$. Comparing this with $\Omega_b h^2 = 0.019 \pm 0.0024$ (95%cl, Burles et. al 1999), we find that a 50% white dwarf halo exceeds the baryon budget ($\frac{\Omega_{MACHOs}}{\Omega_b} \sim 2h$) even before considering the effects of processing most of the baryons through an early star phase. A 20% white dwarf halo is also difficult to reconcile with the above estimate of Ω_b , since the contributions of the progenitor stars will exceed Ω_b .

Many authors have explored the implications of a halo filled with white dwarfs. These analyses, combined with the estimates of the total mass in the halo, make the possibility of a white dwarf halo even less tenable. There are several factors to consider in evaluating such models.

First, the initial mass function (IMF) of the progenitor stars must be markedly different than the disk IMF (Adams & Laughlin 1996, Chabrier, Segretain & Mera 1996). Limits on the IMF arise from both low and high mass stars. Low mass stars ($< 1M_\odot$) would still be burning hydrogen today and should be visible. High mass stars ($> 8M_\odot$) would have evolved into Type II supernovae, ejecting heavy metals back into the interstellar medium¹. From limits on red dwarfs in the halo and the galactic metallicity, Adams & Laughlin 1996, Chabrier, Segretain & Mera 1996 find that the IMF must be sharply peaked about a progenitor star mass of $m \sim 2M_\odot$. Adams & Laughlin conclude that even with the above IMF, the white dwarf contribution to the halo is limited to less than 25% (with 50% being an extreme upper limit).

Next, the metal enriched gas produced when these stars become white dwarfs will pollute the remaining unprocessed gas, leading to high metallicities predicted for the Galactic disk and the interstellar medium (into which much of this gas must be blown out since the total mass in processed gas is much larger than the mass of the disk)(Fields, Matthews & Schramm 1997). Gibson & Mould (1997) have estimated that the expected amount of C, N and O produced would be difficult to reconcile with that in pop II white dwarfs.

The white dwarfs in the halo would also produce heavy metals via Type Ia supernovae. Canal, Isern and Ruiz-Lapuente (1997) use this to limit the halo fraction in white dwarfs to less than 5–10% (or a total

mass in white dwarfs of $5-10 \times 10^{10} M_\odot$). In addition, deep galaxy counts limit the fraction of the halo in white dwarfs, since the brightly burning progenitor stars would be visible (Charlot & Silk). Finally, it is worth mentioning that an all white dwarf halo would rule out the existence of other dark matter in the Universe (for example cold dark matter) (Gates & Turner 1994), opening the door to a host of problems with large scale structure formation.

3. A New Component of the Galaxy

Given the evidence for a previously undetected population of white dwarfs and the severe constraints on a halo population consistent with this evidence we propose a new component of the Galaxy. Such a component was first considered by the authors (Gyuk & Gates 1999) in the context of attempting to lower the mass estimates for the MACHO lenses, and in Gates, Gyuk, Holder & Turner 1998 in considering dark extensions to known components.

This new component is essentially a very thick (scale height > 2 kpc) population of (mostly) old white dwarf stars. It is distinct from known galactic populations, both in distribution and age. This “extended protodisk” extends beyond the thin and thick disk populations, but lies well within the halo. While the details of the distribution cannot be determined without significantly more data, the general features of this proposed model can be illustrated with the following example:

Consider an exponential disk with a volume density given by

$$\rho(r, z) = \frac{\Sigma_0}{2h_z} \exp(-(r_0 - r)/r_d) \text{sech}^2(z/h_z) \quad (1)$$

where $r_d = 4.0$ kpc is the scale length and $h_z = 2.5$ kpc is the scale height. We assume standard values for the position and circular velocity of the Sun, $r_0 = 8.0$ kpc and $v_c = 220$ km/s.

We also assume a velocity structure, which includes a rotational component $\tilde{v}_\phi = 170$ km/s, of the form

$$f = \frac{\rho(r, \phi, z)}{m} \frac{1}{\sqrt{(2\pi)^3 \sigma_r \sigma_\phi \sigma_z}} e^{-\left[\frac{v_r^2}{2\sigma_r^2} + \frac{(v_\phi - \tilde{v}_\phi)^2}{2\sigma_\phi^2} + \frac{v_z^2}{2\sigma_z^2}\right]} \quad (2)$$

where the velocity ellipsoid varies as

$$\sigma_z^2 = 2\pi G \rho_0 h_z^2 = \pi G \Sigma_0 h_z. \quad (3)$$

¹However, Venaktesan, Olinto & Truran 1999 have argued that the bounds on high mass stars are significantly relaxed for progenitor stars with very low ($10^{-4} Z_\odot$) or zero metallicity.

toward the LMC of $\tau \sim 3 - 5 \times 10^{-7}$ for the halo model. The same number of detected white dwarfs corresponds to a lower optical depth (and a smaller total mass in white dwarfs) in our fat disk model.

Finally, the smaller mass in white dwarfs today implies a smaller total mass in the progenitor population. For our above example the progenitor mass $M_{Pstars} \sim 3.5 \times 10^{11} M_{\odot}$, a crucial factor of 10 less than that for a 50% white dwarf halo, assuming the same IMF in both cases.

There are several predictions of this model that can eventually allow it to be distinguished from a standard halo white dwarf population. First, the LMC optical depth cannot be much greater than about 1.5×10^{-7} . Thus if the MACHO and EROS observations toward the LMC remain greater than 2.0×10^{-7} as the statistics improve, this model would be ruled out. Second, because the lenses are concentrated closer to the plane of the galaxy, the typical lens-observer distance will be smaller (of order 5 kpc). This in turn implies an increase in the expected number of parallax events (Gyuk & Gates 1999). Finally, the ratio of optical depths toward the Small and Large Magellanic Clouds is expected to be of order $\tau_{SMC}/\tau_{LMC} \sim 0.8$, in contrast with $\tau_{SMC}/\tau_{LMC} \sim 1.5$ (Sackett & Gould 1993) predicted for a standard halo.

The distribution of event durations (Gyuk & Gates 1999) and a detailed comparison of the distribution (in direction and magnitude) of the observed proper motions will also differ for a halo vs. extended protodisk white dwarf population, but these seem unlikely to be able to differentiate between models without significantly more data.

4. Model Implications

Because the total mass in the white dwarf population today is significantly lower in this model, some of the constraints on a halo white dwarf population can be evaded, including those which consider the progenitor population and the ejected metal enriched gas. The total mass in this new component represents only about 4% of a total halo mass of 2×10^{12} . Since essentially all of the current constraints on white dwarf halos which limit the halo mass fraction in white dwarfs do so at only the 10% level, these constraints can be

sumptions made for the IMF and age of the white dwarf progenitor population.

satisfied by our model. This includes the Type Ia supernovae constraints which are dependent on the mass in white dwarfs today, and cannot be evaded by scenarios which involve somehow hiding the metal enriched gas produced by the progenitor stars.

However, there remains much work to be done to more carefully consider the implications of this new component. First, we still require an IMF which differs significantly from the disk IMF. Assuming a log-normal distribution, Adams & Laughlin 1996 and Chabrier, Segretain & Mera 1996 used conservative constraints to limit the mass fraction of the high and low mass end of the progenitor IMF for a halo white dwarf population. While the lower total mass in our progenitor population will relax the constraints (which are based on the metallicity of the Galactic disk) somewhat at the high mass end, the mass fraction of low mass ($m < 1 M_{\odot}$) stars is constrained by number counts of faint low mass stars locally. The extended protodisk has an increased local density relative to a halo distribution, but a lower total mass, resulting in a constraint similar to that for a halo. Thus we expect to require a fairly sharp low mass drop-off in the progenitor IMF. The implications of such an IMF, including the lower fraction of primordial baryons which is processed through this early population, need to be examined in greater depth.

This new component also provides some intriguing hints for cosmology. When did this component form and how is it related to galaxy formation scenarios? Can this early starburst population help us to trace the baryons in the Universe from their primordial state to the present, where we find most of the baryons in the intracluster medium?

5. Conclusions

We have argued that the microlensing data toward the LMC, combined with observations of white dwarf stars in a proper motion study of the HDF indicate the presence of a new component of the galaxy. This component can be generally described as an extended distribution that extends at least 2 kpc above the galactic plane, but resides well within the halo. It is consistent with all data and observations of the structure and kinematics of the galaxy, and significantly alleviates the considerable problems with a halo population of white dwarf stars that is consistent with microlensing data. Much work remains to carefully consider the implications of such a component,

in particular the formation and evolution of the early population of progenitor stars (and resulting metal enriched gas) that produced this component. However, the significantly lower mass in the progenitor population as compared to that for a halo population of white dwarfs will allow a reasonable fraction of the baryonic mass of the Universe to remain in gas that has not been processed through these very early stars. Moreover, this component may be a more reasonable distribution for the remains of an early starburst population, in which one would expect a more condensed distribution than that of the halo.

This work was supported in part by the DOE (at Chicago and Fermilab) and by the NASA (through grant NAG5-2788 at Fermilab). E. G. would like to thank F. Adams, A. Gould, M.S. Turner and L. Widrow for useful conversations. GG wishes to thank the Research Corporation and Department of Energy (grant DEFG0390ER40546) for partial support.

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